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BREAKUP PROCESSES IN THE $^{28}\text{Si}(\alpha, \text{tp})$ REACTION AT $E_\alpha = 120$ MeV

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Proton–triton coincidence data from the reaction $^{28}\text{Si}(\alpha, \text{tp})$ at $E_\alpha = 120$ MeV show, in addition to contributions from direct breakup and stripping to unbound states, a process which is strongly forward peaked for $E_t < 63$ MeV. This process has a maximum cross section for excitations of the target system in the region of $15 < E_x < 45$ MeV. The data are most likely due to direct inelastic breakup with a proton spectator. The pt coincidence yield at $\theta_t = 10^\circ$ accounts for about 50% of the inclusive continuum (α, t) cross section at $\theta_t = 10^\circ$.

In this paper we report on an investigation of the $^{28}\text{Si}(\alpha, \text{tp})$ reaction at $E_\alpha = 120$ MeV to identify the various processes leading to the continuum part of the inclusive (α, t) spectrum, to determine their contribution to the inclusive triton yield and to find out to what extent α and ^3He projectile breakup differ. Such effects can originate from the large difference in binding energy and/or from the absence of well-defined excited states in ^3He , whereas several excited states are known in ^4He . As will be shown α -breakup does indeed show a process which is absent in the corresponding ^3He breakup reactions.

At 15–40 MeV/amu direct projectile breakup into a spectator and a participant was found to be the dominant reaction mechanism for ^3He projectile breakup [1–5]. The relatively large binding energy of the α -particle can diminish the cross sections for direct breakup reactions considerably [5] and explains why at $E_\alpha = 65$ MeV hardly any direct breakup processes are observed [6]. At $E_\alpha = 160$ and 172.5 MeV bump shaped enhancements centred around beam velocity energies have been observed [7,8] at forward angles in inclusive p, d, t and ^3He spectra. They were therefore attributed to breakup processes. In pt coincidences elastic breakup was identified [9].

In the experiments a self-supporting ^{nat}Si target (92% ^{28}Si) with a thickness of 2.38 mg/cm² was used, for reasons discussed in ref. [1]. With the triton detector fixed at $\theta_t = -10^\circ$ an in-plane tp angular correlation has been measured in which the proton detector

covered the angular range $13^\circ < \theta_p < 149^\circ$ and $-141^\circ < \theta_p < -26^\circ$. The forward-angle telescopes consisted of a 0.3 mm surface barrier ΔE -detector and a 15 and 10 mm hyperpure Ge E -detector for inclusive and correlation experiments, respectively. At more backward angles the telescopes contained three silicon detectors with thicknesses of 0.1, 2 and 5 mm, respectively. At very backward angles ($|\theta_p| > 90^\circ$) protons are by far the most abundant particles and therefore in this region a single E -detector with a thickness of 5 mm was used as well.

Fig. 1a shows the inclusive triton spectrum from the (α, t) reaction at $\theta_t = 10^\circ$. One observes in addition to the sharp peaks resulting from direct proton transfer, a broad bump centred at about 85 MeV and a flat part extending to very low energies. In comparison with the $^{28}\text{Si}(^3\text{He}, \text{d})$ inclusive spectrum of ref. [1] the bump part at its maximum is about a factor of five weaker whereas the flat part has a similar strength. Thus qualitatively the inclusive (α, t) spectrum resembles the $(^3\text{He}, \text{d})$ one but as we will show our coincidence measurements indicate that the interpretation of the spectra differs greatly. Specifically the bump part in the $(^3\text{He}, \text{d})$ case is due to direct breakup whereas in the (α, t) case the bump is predominantly due to proton-transfer reactions.

The triton spectra in figs. 1b–1e are obtained by gating on different parts of the Q -value spectrum. The projections on the triton energy axis of events along the ground-state locus ($Q \simeq -20$ MeV) at $\theta_p = 13^\circ$

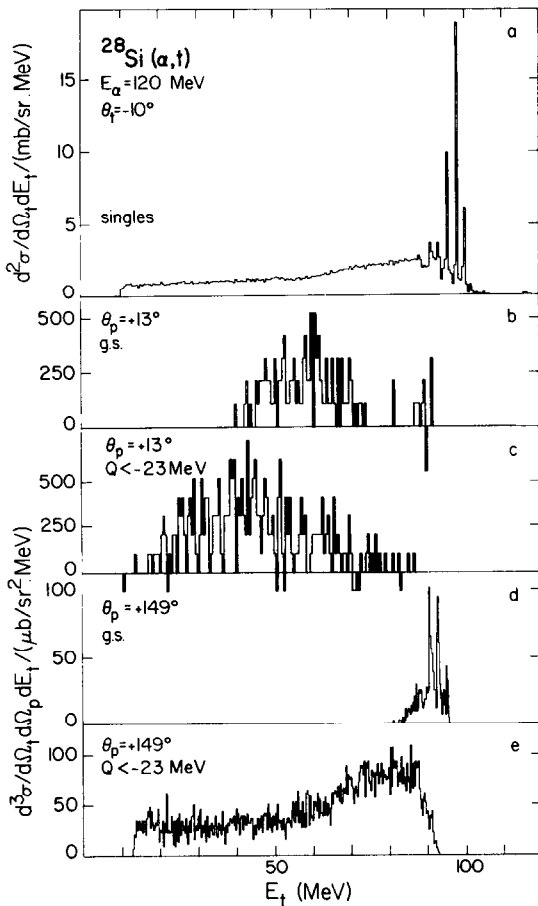


Fig. 1. Comparison between the singles triton spectrum from the reaction $^{28}\text{Si}(\alpha, t)$ at $E_\alpha = 120$ MeV and $\theta_t = -10^\circ$ (a) and the projected triton spectra of the $^{28}\text{Si}(\alpha, pt)$ reaction at $\theta_t = -10^\circ$, for two gates in the Q -value spectrum and the proton angles $\theta_p = +13^\circ$ (b and c) and $\theta_p = +149^\circ$ (d and e).

and $+149^\circ$ are presented in figs. 1b and 1d, respectively. In fig. 1b the bump centred at about $E_t = 60$ MeV, is interpreted as being due to a breakup mechanism in which the proton is spectator and the triton is quasi-free elastically scattered [1,4] (elastic breakup). Obviously this process mainly contributes to the flat part of the inclusive (α, t) spectrum. The more pronounced shift in the centroid energy for the participant triton, compared to the one for the participant deuteron in the corresponding $(^3\text{He}, dp)$ reaction, reflects the difference in projectile binding energy.

At $\theta_p = +149^\circ$ the projection on the triton energy axis of the locus of the ground state and the first ex-

cited state of ^{28}Si (inelastic breakup) yields a spectrum that is dominated by sharp peaks due to the proton stripping to high-lying states in ^{29}P which subsequently decay by proton emission (transfer-decay). These states also show up in the inclusive (α, t) spectrum and in the inclusive and coincident deuteron spectra in the $^{28}\text{Si}(^3\text{He}, d)$ reaction at 52 MeV [1,4].

Figs. 1c and 1e represent the triton spectra obtained by setting a gate on those events which have a $Q < -23$ MeV (i.e. excluding the ground state and first excited state). At $\theta_p = +149^\circ$ the triton spectrum (fig. 1e) shows a bump around 80 MeV and a flat part extending to low energies. The high-energy side of this spectrum contains contributions from transfer-decay. The coincident proton spectra at this angle and gate show an exponential slope which is for $E_t < 82$ MeV almost independent of the triton energy. Thus these data strongly suggest an absorptive breakup process [1,4] with the triton being spectator. The fact that the position of the triton bump does not occur at beam-velocity energy can be understood qualitatively by considering the product of internal momentum distribution and available phase space, becoming zero for $E_t > 93$ MeV. This strongly suppresses the yield in the upper part of the triton spectrum [5].

The processes discussed so far are similar to those already observed in ^3He breakup, the main difference being due to the large difference in binding energy. The spectrum at $\theta_p = 13^\circ$ (fig. 1c), however, shows a new feature: a broad bump around $E_t = 40$ MeV. In contrast to the corresponding deuteron spectra in ^3He breakup where the shape of the spectrum hardly changes with proton angle, this spectrum differs considerably in shape and magnitude from the spectrum at $\theta_p = 149^\circ$ (fig. 1e).

To further investigate this feature we present in fig. 2 angular correlations for events with $Q < -23$ MeV and θ_t fixed at $\theta_t = -10^\circ$ for four energy intervals in the triton spectrum. The correlation for the high-energy bites presented in fig. 2b and 2c are rather isotropic. The events in the energy interval $63 < E_t < 82$ MeV (fig. 2b) are predominantly due to absorptive breakup; those with $82 < E_t < 96$ MeV (fig. 2c) correspond mainly to transfer-decay. The angular correlations are in agreement with such processes [4]. The correlation in fig. 2a, however, shows a forward peaked anisotropic component on top of a much lower isotropic part presumably due to absorptive breakup.

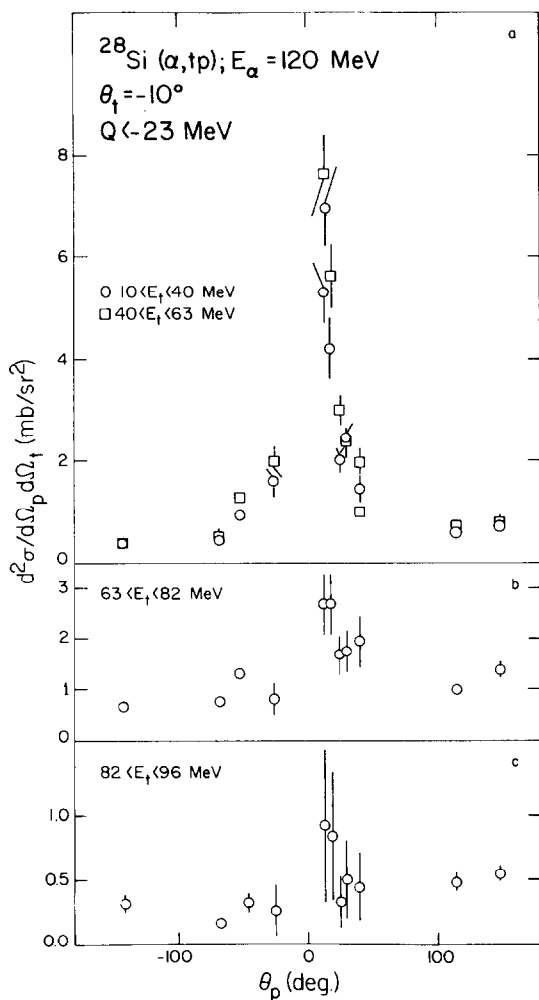


Fig. 2. Angular correlation for tp coincidences with θ_t fixed at $\theta_t = -10^\circ$ and $Q < -23$ MeV for various energy intervals in the triton energy.

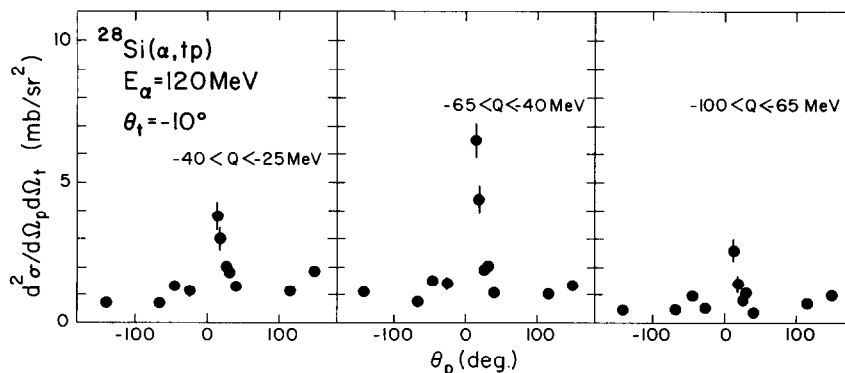


Fig. 3. Angular correlation for tp coincidences with θ_t fixed at $\theta_t = -10^\circ$ for various intervals in the Q -value spectrum.

Such strongly forward peaked components have been observed before by Koontz in the coincidences between p, d, t and ^3He , and low-energetic p and α [10].

Moreover, the intensity ratio of the anisotropic over the isotropic component in the tp angular correlation has, as shown in fig. 3, a maximum for the Q -value interval $-65 < Q < -40$ MeV. In the analysis of the anisotropic component at $\theta_p = 13^\circ$ we constructed event-by-event the pt relative energy spectrum. This spectrum shows a broad peak at energies corresponding to $21 < E_x < 26$ MeV in ^4He , where several broad states are known.

From these observations we propose the following processes as possible mechanisms leading to the anisotropy in the tp angular correlation:

- (i) The reaction (α, α^*) in which α^* represents a state in the excitation-energy range $21 < E_x < 26$ MeV.
- (ii) Quasi-free inelastic breakup of the α -particle in which the proton is spectator and the participant triton has an inelastic scattering with the target nucleus.

In both processes the angular correlation will be forward peaked and the residual ^{28}Si nucleus is excited to predominantly $15 < E_x < 40$ MeV. The (α, α^*) process has been observed at $E_\alpha = 65$ MeV where α^* stands for the $J^\pi = 0^+$ state at $E_x = 20.1$ MeV. In the present experiment even at the smallest relative angle of 16° this state cannot be observed.

Both processes implement that a similar anisotropy will show up in pt angular correlations with θ_p fixed at $\theta_p = -10^\circ$ and θ_t variable and $d_1 d_2$ correlations with $\theta_{d_1} = -10^\circ$ and θ_{d_2} variable. In case of the (α, α^*) reaction the decay of the α^* into either p + t or d + d will occur after the Si nucleus has been excited and hence one expects that the anisotropic components in

Table 1

Intervals in particle energy and Q -value in tp, pt and dd correlations, for which the cross section ratio anisotropic over isotropic component is optimal.

$\theta = -10^\circ$	θ_{var}	Energy range (MeV) for particle detected at $\theta = -10^\circ$	Q -value interval (MeV)
t	p	$10 < E_t < 63$	$-65 < Q < -40$
p	t	$15 < E_p < 45$	$-65 < Q < -40$
d	d	$30 < E_d < 70$	$-36 < Q < -26$

all three correlations (tp, pt and dd) will peak in the same Q -value interval. For the quasi-free process however a less negative Q -value is expected in the dd case because the target nucleus will be less excited due to the lower initial energy of the participant: $E_d \sim 35$ MeV versus $E_t \sim 70$ MeV.

The experimental results for these correlations, listed in table 1, seem to favour the quasi-free process. However, one should keep in mind that the branching ratio for pt decay and dd decay of excited states in ^4He is strongly in favour of the pt. Therefore it can not be ruled out that the sequential-decay mode still dominates in the tp and pt correlation data, whereas the d-d data are predominantly due to the quasi-free process. We intend to further investigate this anisotropic component via tp angular correlations with detectors in a close geometry such that the sharp $E_x = 20.1$ MeV state in ^4He can be observed.

Table 2

Comparison between the cross section (mb/sr) for the continuum part of the inclusive triton spectrum and the contributions from various tp coincidence processes measured in the reaction $^{28}\text{Si}(\alpha, t)$ at $E_\alpha = 120$ MeV and $\theta_t = -10^\circ$. The contribution of the coincidence cross sections have been obtained by integrating over the proton angle.

	$10 < E_t < 40$ MeV	$40 < E_t < 63$ MeV	$63 < E_t < 82$ MeV	$82 < E_t < 96$ MeV	$10 < E_t < 96$ MeV
<i>coincidences</i>					
elastic breakup (0^+)	< 0.2	1.7 ± 0.6	1.8 ± 0.5		3.4 ± 0.7
inelastic breakup (2^+)	0.25 ± 0.20	0.45 ± 0.13	0.69 ± 0.17		1.4 ± 0.3
absorptive breakup					
isotropic component	10 ± 2	11 ± 3	13 ± 5		34 ± 6
anisotropic component	3.4 ± 1.3	4.0 ± 1.5	< 1	< 0.3	7.4 ± 2.0
transfer-decay			4.5 ± 3	15 ± 3	19 ± 5
total	14 ± 2	17 ± 3	20 ± 4	15 ± 3	66 ± 6
singles	28 ± 3	28 ± 3	37 ± 4	33 ± 4	126 ± 8

Integration of the angular correlations over angle, assuming a linear ϕ -dependence (see e.g. refs. [1,2,4]), allows a comparison of the cross section of the continuum part of the inclusive triton spectrum at $\theta_t = -10^\circ$ and the cross sections obtained in the pt angular correlations with θ_t kept fixed at $\theta_t = -10^\circ$. The results for the tp coincidences, listed in table 2 for various triton energy bites, account for about 50% of the inclusive triton spectrum. These values have been corrected by about 10–20% for the low-energy cutoff by the ΔE counter in the forward proton telescope. These corrections are based on the proton spectra at backward angles and were found to have only a minor influence on the shape of the triton spectra in e.g. fig. 1c. Rough estimates of other triton charged-particle cross sections lead to a total of about 70–80%, indicating that tn coincidences should be responsible for about 25% of the yield at $\theta_t = -10^\circ$.

Thus tp coincidences are the major contributor to the inclusive triton yield at $\theta_t = 10^\circ$. The contribution originates from elastic, inelastic and absorptive quasi-free breakup and the transfer-decay process. In addition one observes a strongly forward peaked process in which the residual system is preferably excited to 15–40 MeV. The features of this process are consistent with a quasi-free inelastic scattering process in which the proton is spectator and the triton is participant, but the sequential decay of an α -particle excited to 22–26 MeV cannot be excluded.

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